

Beauty in the Standard Model and Beyond

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Abstract. The study of CP violation in the B system allows us to perform quantitative tests of the CP symmetry in the Standard Model. Many precise measurements of the sides and angles of the Unitarity Triangle used to test the theory are made possible by the abundant experimental data accumulated at the B factories and the Tevatron. I review the Standard Model description of CP violation and the key measurements which allow us to use CP violation studies as a probe for New Physics.

Keywords: CP violation, Unitarity Triangle, B physics

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INTRODUCTION

CP violation plays a fundamental role in the explanation of the matter-dominated universe [1]. In the Standard Model, CP violation occurs in weak interactions due to the complex phase in the quark mixing matrix, the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. This description of CP violation, known as the CKM mechanism, provides an elegant and simple explanation of this phenomenon, and is in agreement with the experimental measurements in the kaon and B sectors. However, the CKM mechanism fails to account for the observed baryon-to-photon density ratio in the Universe. This suggests that other sources of CP violation must exist besides the CKM mechanism, and that CP violation studies may be used as probes for New Physics. The key for these studies is to measure CP violation in channels that are theoretically very well understood in the Standard Model, and look for deviations from the expectation.

A convenient tool for these studies is given by the Unitarity Triangle (UT), illustrated in Fig. 1. All sides and angles of the UT can be measured in the study of B decays: the time-dependent CP asymmetries measure the angles, while the sides can be determined

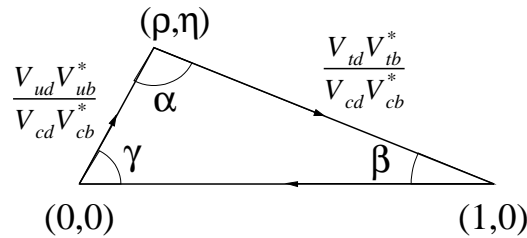


FIGURE 1. The Unitarity Triangle.

by the measurements of the semileptonic B decays and the B mixing. Since one of the sides of the UT is normalized to a known quantity, only two measurements are necessary to define the triangle (e.g. the two sides). Any additional measurement (e.g. an angle) can therefore be used to test the CKM mechanism: any inconsistency can be interpreted as a sign of New Physics. Alternatively, we can look for New Physics by measuring the same quantity (an angle or a side) through channels that have different sensitivity to New Physics. It is important to note that precision and redundancy are essential for testing the theoretical predictions.

The asymmetric B factories at SLAC and KEK were specifically designed for such measurements. In these machines, electrons and positrons collide at $\sqrt{s} \approx 10$ GeV and produce an $\Upsilon(4S)$ resonance which decays into a $B\bar{B}$ pair. The clean environment, typical of e^+e^- colliders, allows the two experiments, *BABAR* and *Belle*, to reconstruct B decays with very high purity and reconstruction efficiency.

The two Tevatron experiments, CDF and DØ, study B hadrons produced in $p\bar{p}$ collisions at $\sqrt{s} \approx 2$ TeV. The harsher experimental environment is compensated by the large boost of the B mesons in the laboratory frame and the fact that all B hadrons can be produced. The Tevatron B physics program is therefore complementary to the programs at the B factories.

MEASUREMENT OF THE ANGLES

At the B factories, the angles of the Unitarity Triangle can be precisely determined through the measurement of the time dependent CP asymmetry, $A_{CP}(t)$:

$$A_{CP}(t) \equiv \frac{N(\bar{B}^0(t) \rightarrow f_{CP}) - N(B^0(t) \rightarrow f_{CP})}{N(\bar{B}^0(t) \rightarrow f_{CP}) + N(B^0(t) \rightarrow f_{CP})}, \quad (1)$$

where $N(\bar{B}^0(t) \rightarrow f_{CP})$ is the number of \bar{B}^0 that decay into the CP -eigenstate f_{CP} after a time t . If only one amplitude contributes to the decay, $A_{CP}(t)$ can be written as

$$A_{CP}(t) = -\eta_f \text{Im}(\lambda) \sin(\Delta m t), \quad (2)$$

where Δm is the difference in mass between B mass eigenstates and η_f is the CP eigenvalue of the final state. For some decays, $\text{Im}(\lambda)$ is directly and simply related to an angle of the UT. For example, in the decay $B \rightarrow J/\psi K^0$, $\text{Im}\lambda = \sin 2\beta$.

The measurement of $A_{CP}(t)$ utilizes decays of the $\Upsilon(4S)$ into two neutral B mesons, of which one is completely reconstructed into a CP eigenstate, while the decay products of the other identify its flavor at decay time. The time t between the two B decays is determined by reconstructing the two B decay vertices. The CP asymmetry amplitudes are determined from an unbinned maximum likelihood fit to the decay time distributions separately for events tagged as B^0 and \bar{B}^0 .

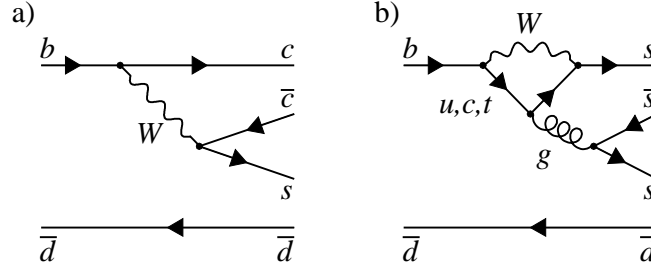


FIGURE 2. Feynman diagrams that mediate the B^0 decays used to measure the angle β : a) $B^0 \rightarrow$ charmonium + K^0 ; b) penguin dominated B decays.

Measurement of the angle β

The decays $B^0 \rightarrow$ charmonium + K^0 , known as “golden modes” for the measurement of the angle β , are dominated by a tree level diagram $b \rightarrow c\bar{c}s$ with internal W boson emission (Fig. 2a). Besides the theoretical simplicity, these modes are advantageous because of their relatively large branching fractions ($\sim 10^{-4}$) and the presence of the narrow J/ψ resonance in the final state, which provides a powerful rejection of combinatorial background. The CP eigenstates considered for this analysis are $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$ and $J/\psi K_L$.

The results for the measurements of CP violation in $B^0 \rightarrow$ charmonium + K^0 are illustrated in Fig. 3 (left). The asymmetry between the Δt distributions of events tagged as B^0 and events tagged as \bar{B}^0 , clearly visible in a) and c), is a striking manifestation of CP violation in the B system. The corresponding time dependent CP asymmetry is shown in b) and d). *BABAR* measures $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$ [3]. When combining this result with the corresponding measurement from the Belle experiment $\sin 2\beta = 0.652 \pm 0.039 \pm 0.020$ [4], we obtain $\sin 2\beta = 0.685 \pm 0.032$ [5]. This implies that the angle β is known to a precision of 1 degree.

In the Standard Model, final states dominated by $b \rightarrow s\bar{s}s$ or $b \rightarrow s\bar{d}d$ decays offer a clean and independent way of measuring $\sin 2\beta$ [6]. Examples of these final states are ϕK^0 , $\eta' K^0$, $f_0 K^0$, $\pi^0 K^0$, ωK^0 , $K^+ K^- K_S$ and $K_S K_S K_S$. These decays are mediated by the gluonic penguin diagram illustrated in Fig. 2b. With contributions from physics beyond the Standard Model, new particles such as squarks and gluinos could participate in the loop and affect the time dependent asymmetries [7].

The decay $B^0 \rightarrow \phi K_S$ is ideal for these studies. In the Standard Model, this decay is an almost pure $b \rightarrow s\bar{s}s$ penguin decay, and its CP asymmetry is expected to coincide with the one measured in charmonium + K^0 decays within a few percent [7]. Experimentally, this channel is also very clean, thanks to the powerful background suppression due to the narrow ϕ resonance. Unfortunately, the branching fraction for this mode is quite small ($\approx 8 \times 10^{-6}$), therefore the measurement is limited by a large statistical error.

The decay $B^0 \rightarrow \eta' K_S$ is favored by a larger branching fraction ($\approx 6 \times 10^{-5}$). In the Standard Model, this decay is also dominated by penguin diagrams; other contributions are expected to be small [8].

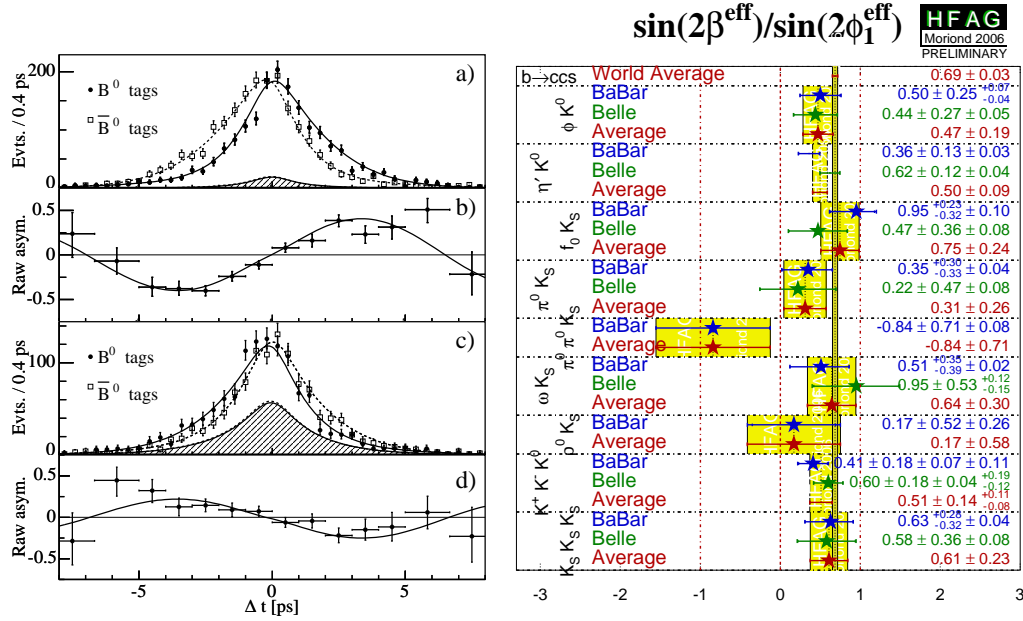


FIGURE 3. Left: *BABAR* measurement of $\sin 2\beta$ in the “golden modes”. Plot a) shows the time distributions for events tagged as B^0 (full dots) or \bar{B}^0 (open squares) in CP odd (charmonium K_S) final states. Plot b) shows the corresponding raw CP asymmetry with the projection of the unbinned maximum likelihood fit superimposed. Plots c) and d) show the corresponding distributions for CP even ($J/\psi K_L$) final states. Right: measurements of $\sin 2\beta$ in penguin dominated modes.

A summary of the measurements of $A_{CP}(t)$ in penguin modes [9, 10, 11, 12, 13, 4] by the *BABAR* and Belle experiments is reported in Fig. 3 (right). The naive averaging of all the penguin modes [5] results in a 2.5σ deviation from the value of $\sin 2\beta$ measured in the golden mode. However, this discrepancy has to be interpreted with caution since each mode can be affected by new physics in different ways.

Measurement of the angles α and γ

The most accurate determination of the angle α comes from the measurement of the time-dependent CP asymmetry in $B^0 \rightarrow \rho^+ \rho^-$ decays. In the SM, these decays are dominated by a $b \rightarrow u\bar{u}d$ tree diagram. In the assumption that no other diagram contributes to the final state, $\text{Im}\lambda = \sin 2\alpha$. Penguin diagrams can contribute to this final state, but their contribution is thought to be small because of the small branching fraction measured for the $B^0 \rightarrow \rho^0 \rho^0$ decay [14]. Since ρ is a vector meson, the $\rho^+ \rho^-$ final state is characterized by three possible angular momentum states, and therefore it is expected to be an admixture of $CP = +1$ and $CP = -1$ states. However, polarization studies [15, 16] indicate that this final state is almost completely longitudinally polarized, and therefore almost a pure $CP = +1$ eigenstate. The parameter $\sin 2\alpha$ is therefore measured from the amplitude of the time dependent CP asymmetry, using the same technique described for

the measurement of the angle β .

Other final states, such as $B^0 \rightarrow \pi^+\pi^-$ and $B \rightarrow \rho\pi$ [17, 18], provide additional constraints on the angle α . Combining all *BABAR* and *Belle* results, we measure $\alpha = (105^{+15}_{-9})^\circ$ [19].

The angle γ is measured exploiting the interference between the decays $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow \bar{D}^0 K^+$, where both D^0 and \bar{D}^0 decay to the same final state. This measurement can be performed in three different ways: utilizing decays of D mesons to CP eigenstates [20]; utilizing doubly Cabibbo-suppressed decays of the \bar{D} meson [21]; exploiting the interference pattern in the Dalitz plot of $D \rightarrow K_S \pi^+ \pi^-$ decays [22]. Currently, the last analysis provides the best measurement of the angle γ . Combining all results from *BABAR* and *Belle*, we measure $\gamma = (65 \pm 20)^\circ$ [23].

MEASUREMENT OF THE SIDES

The left side of the Unitarity Triangle is determined by the ratio of the CKM elements $|V_{ub}|$ and $|V_{cb}|$. Both elements are measured in the study of semi-leptonic B decays. The measurement of $|V_{cb}|$ is already very precise, with errors of the order of 2% [5]. The determination of $|V_{ub}|$ is more challenging, mainly due to the large background coming from $b \rightarrow c\ell\nu$ decays, about 50 times more likely to occur than $b \rightarrow u\ell\nu$ transitions.

Two approaches, inclusive and exclusive, can be used to determine $|V_{ub}|$. In inclusive analyses of $B \rightarrow X_\ell \ell \nu$, the $b \rightarrow c\ell\nu$ background is suppressed by cutting on a number of kinematical variables. This implies that only partial rates can be directly measured, and theoretical assumptions are used to infer the total rate and extract $|V_{ub}|$. The theoretical error associated with these measurements is $\approx 4\%$. Averaging all inclusive measurements from the *BABAR*, *Belle*, and *CLEO* experiments we determine $|V_{ub}| = (4.45 \pm 0.33) \times 10^{-3}$ [5], where the error includes statistical, systematic and theoretical errors.

In exclusive analyses, $|V_{ub}|$ is extracted from the measurement of the branching fraction $B \rightarrow \pi \ell \nu$. These analyses are usually characterized by a good signal/background ratio, but lead to measurements with large statistical errors due to the small branching fractions of the mode studied. In addition, the theoretical errors, dominated by the uncertainties in the form factor calculation, are $\approx 12\%$. Both experimental and theoretical errors are expected to decrease in the future, making this approach competitive with the inclusive method.

The right side of the Unitarity Triangle is determined by the ratio of the CKM elements $|V_{td}|$ and $|V_{ts}|$. This ratio can be determined with small theoretical uncertainty from the measurement of ratio of the B^0 and B_s mixing frequencies. While the B^0 mixing parameter Δm_d has been measured very precisely by many experiments [5], the B_s mixing parameter Δm_s had escaped detection until recently, due to the difficulty in detecting its very fast oscillations. This spring, the Tevatron experiments succeeded in this endeavor, and published evidence for B_s oscillations [24, 25], as described in detail in [26]. The value of Δm_s measured by CDF is $17.33^{+0.42}_{-0.21} \pm 0.07 \text{ps}^{-1}$. Combining this measurement with the world average for Δm_d , one can extract $|V_{td}/V_{ts}| = 0.208^{+0.008}_{-0.007}$.

CONCLUSION

Precise and redundant measurements of the sides and angles of the Unitarity Triangles have provided a crucial test of CP violation in the Standard Model. The constraints on the (ρ, η) plane due to the measurements described in this article are illustrated in Fig. 4. The comparison shows excellent agreement between all measurements, as predicted by the CKM mechanism.

Measurements of time-dependent CP violation asymmetries in penguin-dominated modes are sensitive to contributions from physics beyond the Standard Model. These measurements are still heavily dominated by statistical errors and will benefit greatly from a factor two increase in statistics that both *BABAR* and Belle are planning to achieve by 2008.

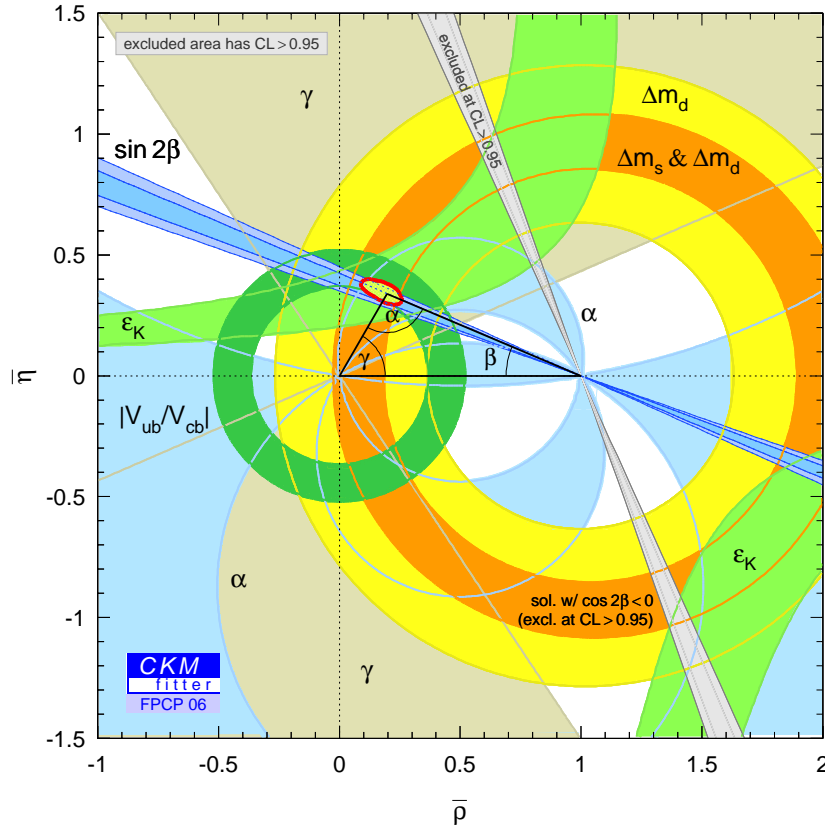


FIGURE 4. Constraints on the apex of the Unitarity Triangle resulting from the various measurements of its sides and angles.

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